A Young Very Low-Mass Object surrounded by warm dust

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ABSTRACT

We present a complete low-resolution (R$\sim$100) near-infrared spectrum of the substellar object GY 11, member of the ρ-Ophiuchi young association. The object is remarkable because of its low estimated mass and age and because it is associated with a mid-infrared source, an indication of a surrounding dusty disk. Based on the comparison of our spectrum with similar spectra of field M-dwarfs and atmospheric models, we obtain revised estimates of the spectral type, effective temperature and luminosity of the central object. These parameters are used to place the object on a Hertzprung-Russell diagram and to compare with the prediction of pre-main sequence evolutionary models. Our analysis suggests that the central object has a very low mass, probably below the deuterium burning limit and in the range 8–12 $M_{Jupiter}$, and a young age, less than 1 Myr. The infrared excess is shown to be consistent with the emission of a flared, irradiated disk similar to those found in more massive brown dwarf and TTauri systems. This result suggests that substellar objects, even the so-called isolated planetary mass objects, found in young stellar associations are produced in a similar fashion as stars, by core contraction and gravitational collapse.

Subject headings: Stars: low-mass, brown dwarfs – Stars: fundamental parameters – Stars: atmospheres – Infrared: stars

1. Introduction

The discovery of Brown Dwarfs (BDs) and objects with masses comparable to those of giant planets, well below the deuterium burning limit ($M<13$ M_J), "free-floating" in

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young stellar clusters (Zapatero-Osorio et al. 2000; Lucas & Roche 2000) has opened an interesting debate on their origin. Do they form like ordinary stars from the collapse of molecular cores (Shu et al. 1987)? If so, the very existence of very low-mass objects and their mass function put strong constraints on star formation theories. Alternatively, BDs and isolated planetary mass objects may be stellar "embryos" ejected from multiple forming systems before reaching a stellar mass (Reipurth & Clarke 2001), or they may form like planets by coagulation of dust particles and subsequent gas accretion within circumstellar protoplanetary disks (Lin et al. 1998). Young (proto)-planets could then be extracted or ejected by dynamical interactions from the forming planetary systems. In this scenario, isolated BDs and planetary mass objects are intrinsically different from stars; their study sheds no light on *star* formation theories, but provides instead a chance of studying the early evolution of giant planets where they can be observed in isolation, rather than very close to a much brighter star.

One way to shed light on the origin of very low mass objects is to ascertain their association with circumstellar disks, which are characteritics of stellar formation from the contraction of a molecular core. Deep images in the L band Muench et al. (2001) and in the mid-infrared (Persi et al. 2000; Bontemps et al. 2001) have shown that many very low luminosity objects have excess emission at these wavelengths, and detailed studies of some of them have proven that the central objects are bona-fide BDs. Their infrared excess is consistent with the presence of a surrounding disk similar to those found around more massive pre-main sequence stars (Comerón et al. 1998, 2000; Natta & Testi 2001). These initial findings, albeit limited, seem to suggest that indeed BDs form like ordinary stars.

We report here the first results of a project aimed on one hand to improve our understanding of disks around BD, following the approach of in Natta & Testi (2001), and on the other hand to find evidence of a circumstellar disk around *bona fide* isolated planetary mass objects. We have used the Near-Infrared Camera and Spectrograph (NICS) on the 3.56m Telescopio Nazionale Galileo to acquire low-resolution (NIR) spectra of a sample of mid-infrared sources located within the ρ-Ophiuchi cloud Bontemps et al. (2001). Our target list included objects detected at 6.7 and 14.3 μm with the ISOCAM camera on board of ISO (Kessler et al. 1996; Cesarsky et al. 1996), having low effective temperature (T_{eff}), luminosity (L_*) and extinction (A_V) based on photometric or limited 2.2 μm spectroscopic estimates. The goal of our new observations was to obtain improved determinations of these parameters and to derive accurate values of masses and ages of the targets by comparison with theoretical evolutionary tracks. The results for the complete sample will be discussed elsewhere (Natta et al. 2002). In this Letter, we report on one of the sources, number 33 of the ISOCAM list of Bontemps et al. (2001), which is associated with the NIR source GY11 (Greene & Young 1992). The substellar nature of this object was already proposed by Rieke

& Rieke (1990) and confirmed by Comerón et al. (1998); Wilking et al. (1999). We derive a new, accurate spectral classification of GY11, and of its effective temperature and luminosity. Our data suggest that GY11 is a planetary mass object, with an infrared excess that can be roughly modeled as due to a circumstellar disk similar to those associated to T Tauri stars. These observations provide the first evidence that objects of such small mass actually form in a star-like manner, and thus that they are genetically different from "planets".

2. Observations

A near-infrared low-resolution spectrum of GY11 was obtained with the Telescopio Nazionale Galileo on La Palma on July 9, 2001, using a $0\farcs5$ slit and the high-throughput low-resolution prism-based disperser unique to NICS (Baffa et al. 2001), the Amici device (Oliva 2000); this setup offers a complete NIR spectrum, 0.85 to 2.35 μm, at R$\sim$100 accross the entire range, and it allows an accurate classification of faint and cool dwarfs (Testi et al. 2001). Instrumental and telluric correction was ensured by observations of A0 stars. The shape of the final spectrum was checked using near infrared photometric measurements from the 2MASS second incremental data release; synthetic magnitudes were computed using the appropriate transmission curves and compared with the source photometry, colors were found to be consistent with those of 2MASS to within 10%, as expected from typical uncertainties. To better constrain the values of the extinction, we also obtained optical i-band (0.77 μm) photometry at the ESO-La Silla 1.54m Danish Telescope using the DFOSC instrument. Photometric calibration was ensured by observations of a set of Landolt (1992) standard stars, converted into the Gunn system using the transformations given by Fukugita et al. (1996).

3. Central source parameters

Bontemps et al. (2001) associated the ISOCAM source 33 with a Class II object member of the ρ-Ophiuchi young stellar cluster known as GY11 (Greene & Young 1992). The brown dwarf nature of GY11 has been suspected for some time (Rieke & Rieke 1990). However, there is a large uncertainty in the literature as to the exact value of its photospheric parameters and mass. Bontemps et al. (2001) estimate bolometric luminosity and extinction to be $L_* \sim 0.001\ L_\odot$, A_V=2.7 mag from NIR photometry. Based on multiband infrared photometry and a 2.2μm low resolution spectrum, Wilking et al. (1999) estimate a spectral type M6.5, $A_V \sim$5 mag, $L_* \sim$0.002 $L_\odot$, and $T_{eff} \sim$2650 K. These authors noted that due to veiling caused by dust emission, the spectral type could easily be some 2–3 subclasses later,

and the extinction significantly underestimated. In fact, Comerón et al. (1998) derive a higher value of A_V=10 mag from broadband photometric measurements that include optical and infrared bands.

Our complete near infrared spectrum offers the possibility of a better estimate of the source parameters, as it allow us to use the global spectrum shape below 2 μm, a region which is less affected by the continuum veiling due to the dust emission. Given the expectation that the surface gravity of very young BDs shouls be similar to sub-giants, we derive the photospheric parameters by comparison with field dwarfs spectra and model atmospheres with appropriate surface gravity, as suggested by the evolutionary models (Comerón et al. 2000). We first derive extinction and spectral type by matching the observed GY11 spectrum with that of field dwarfs in the solar neighborhood (Testi et al. 2002), obtained with the same instrumental set-up and reddened using the Cardelli et al. (1989) extinction law most appropriate for Ophiucus (R_V=4.2; Fig. 1a). We try to provide the best fit to the global shape of the spectrum, with particular attention to the shape of the H-band, the J-band features and the drop due to water vapor absorption at the red edge of the J-band. Overall, the best spectral match is found with the field dwarf with spectral type M8.5 and extinction A_V ∼7.0 mag. Lower values of A_V (by ∼ 1 mag) offer a better match of the spectrum with later dwarf spectra (M9–L0), but are not consistent with the broad band optical measurements (see inset in Fig. 4). A higher value of the extinction causes a too steep rise of the spectrum below 1.2 μm. Field dwarfs with spectral types earlier than M7.5 show large deviations from the observed shape of the H-band and the drop at 1.3 μm. Given the uncertainties of a classification based on objects with very different surface gravity, we expect our classification to be accurate within one spectral class and the visual extinction estimate within one magnitude.

As a second step, in order to derive an estimate of the photospheric effective temperature (Fig. 1a), we compare the observed GY11 spectrum, with reddened, appropriate surface gravity, $\log_{10}(g)$=3.5, model atmospheres (Allard et al. 2000; Chabrier et al. 2000). The best estimate of the effective temperature is ∼2400±100 K. Higher temperature models offer a better match of the H-band shape, but underestimate the drop near 1.3 μm and the global shape of the spectrum at J-band. The derivation of the effective temperature of young dwarfs based on theoretical synthesis of the near infrared spectrum is very uncertain (Lodieu et al. 2002); however, our value of T_{eff} for an object of spectral type M8.5 is consistent with the spectral type vs. effective temperature scale discussed by Wilking et al. (1999), and only marginally higher than the latest effective temperature scales derived for field dwarfs (Leggett et al. 2001).

To estimate the luminosity (L_*) of the object, we used the 2MASS J-band magnitude,

dereddened by $A_V \sim$ 7.0 mag, and the bolometric correction derived from the best fitting (2400 K) atmospheric model. The value of this "theoretical" bolometric correction is nearly identical to the empirical value adopted by Wilking et al. (1999). We derive a value of $L_* \sim 0.008\ L_\odot \pm 30\%$.

Using the L_* and T_{eff} values derived above, we can compare the position of GY11 in the Hertzprung-Russell diagram with the predictions of theoretical pre-main sequence evolutionary models. In Figure 2 we show this comparison for the latest release of evolutionary tracks from three leading groups in the theory of pre-main sequence evolution of substellar objects. In spite of the relatively large uncertainties on L_* and T_{eff}, and on the limited accuracy of pre-main sequence evolutionary tracks at these ages and masses, we confirm that GY11 is a young ($\tau < 1$ Myr), very low mass object, probably below or very close to the deuterium burning limit, with a best mass estimate in the range 7 to 12 $M_{Jupiter}$.

4. Infrared Excess and Disk Models

GY11 is the lowest mass object with a clearly detected infrared excess. It is detected by ISOCAM in the two broad-band filters LW2 and LW3 (λ_{eff} 6.7 and 14.3 μm, respectively) used by (Bontemps et al. 2001) in their ρ Oph survey, as well as in the three intermediate-band filters, SW1, LW1, LW4 (λ_{eff}=3.6, 4.5 and 6.0 μm, respectively), used by Comerón et al. (1998) in their pointed observations of optically identified candidate brown dwarfs. The ISOCAM measurements in the broad- and narrow-bands are in good agreement, within the flux calibration uncertainties, which we assume to be $\sim$ 20%.

As usually with ISOCAM, the $\sim 6''$ beam includes multiple sources seen in higher resolution near-infrared images, which may contribute to the observed fluxes. Figure 3 compares a K_s image of the region around GY11 extracted from the VLT/ESO archive (originally observed as part of ESO proposal 63.I-0691) and the ISOCAM LW1 (λ_{eff}=4.5 μm) image from the ISO archive (Comerón et al. 1998). The mid-infrared emission peaks very close to the position of GY11. Although a small contamination from the NIR source $\sim 8''$ to the east is possible, we think that most of the mid-infrared observed flux comes from GY11; a similar conclusion was also reached by Comerón et al. (1998).

In Figure 4, we show the spectral energy distribution (SED) of GY 11 at all wavelengths and compare it to that of an irradiated, flared disk similar to those that reproduce the observed characteristics of TTauri systems (Chiang & Goldreich 1997). The disk has a dust mass of 1 Earth mass ($\sim$3% of the mass of the central object, for an assumed gas-to-dust mass ratio of 100) and is heated by a a central source with the GY11 temperature, luminosity

and mass. We show the predicted SED when the disk extends inward to the stellar surface (solid line) and when it has an inner hole of 3 stellar radii (dotted line). More details on the disk models can be found in Natta & Testi (2001) and Natta et al. (2002). The agreement between observed and predicted fluxes is rather good, especially for the disk with the large inner hole. In particular, both models predict total (star+disk) fluxes that in the J, H, K bands are smaller than the calibrated TNG fluxes by 15% at most.

As an independent check, we computed optical and NIR broad-band magnitudes from the model-predicted SED. They are compared in the inset of Figure 4 with the observed dereddened magnitudes in i (this paper), R,I,L′ (Comerón et al. 1998), J,H,K (2MASS). The agreement is again quite good.

The ISOCAM measurements, especially that at 14.3 μm, have large error bars, and one should not overinterpret them. However, is of some interest to point out that, if indeed the mid-infrared excess is due to disk emission, the disk must be flared. Therefore, dust and gas must be well mixed, as in the majority of pre-main–sequence stars, and no major settling of the dust onto the disk midplane has occurred during the lifetime of GY11. The disk must be optically thick to mid-infrared radiation; this however sets only a lower limit to the disk mass of roughly 10^{-5}-10^{-6} $M_\odot$ depending on the exact value of the dust mid-infrared opacity and surface density profile. Note that the disk mass has to be very small; if we assume the ratio of the disk mass to the mass of the central object typical of TTS (0.03), then the disk mass is about 3×10^{-4} $M_\odot$, and the disk contains only 1 Earth mass of dust. As a consequence, the accretion rate (if any) is also likely to be low, with an average value over the lifetime of the object that cannot exceed $3{\times}10^{-10}$ $M_\odot\,yr^{-1}$ (for an age of 1 Myr). The accretion luminosity is also small, about 40 times lower than the luminosity of the photosphere. A direct determination of the disk mass can be derived from (sub)millimeter wavelength observations. We predict for GY11 a 1.3mm flux of about 0.6 mJy, which is well below the upper limit set by the survey of Motte et al. (1998), but within the expected capabilities of the ALMA millimeter array.

5. Conclusions

The results presented in this letter show evidence that a young isolated planetary mass objects in ρ-Oph, with mass of about 10 M_J, is surrounded by warm dust, possibly distributed on a disk similar in properties to those around young brown dwarfs and T Tauri stars. The implications of this finding, that should be confirmed by higher spatial resolution mid-infrared observations, and should be extended to a large sample of similar objects, are profound, since it gives a clear indication that isolated BDs and even planetary mass objects

form like stars and are not produced in a planet-like fashion within protoplanetary disks around more massive objects, and later ejected by dynamical interactions. Isolated BDs and planetary mass objects are thus an extension of the stellar and substellar sequence to very low masses and have different origins from “planets”.

This work is partly based on observations collected at the Italian Telescopio Nazionale Galileo, Canary Islands, Spain, at the European Southern Observatory telescopes on La Silla and Paranal observatories, Chile, and on data obtained by the European Space Agency Infrared Space Observatory. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This work was partly supported by ASI grant ARS 1/R/27/00 to the Osservatorio di Arcetri.

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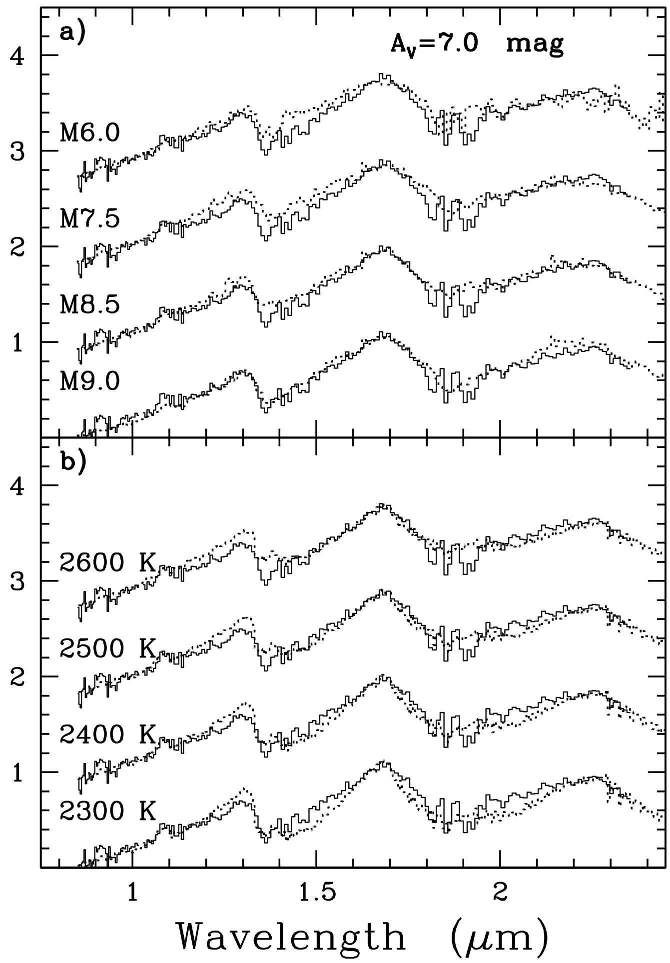

Fig. 1.— The spectrum of GY11 (thick solid line) is compared with reddened spectra of field M-dwarfs (dotted lines) as labelled (from Testi et al. 2002), all spectra are normalized at the mean flux in the 1.6-1.7 μm range and shifted with constant offsets for clarity. The spectrum of GY11 is reproduced at every offset to ease the comparison. b) similar to a), but the dotted spectra are reddened theoretical atmospheric models (Allard et al. 2000), T_{eff} as labelled. In both panels, the observed spectra have a lower signal to noise in the region corresponding to the strong telluric absroption (1.35–1.45 μm and 1.82–1.95 μm).

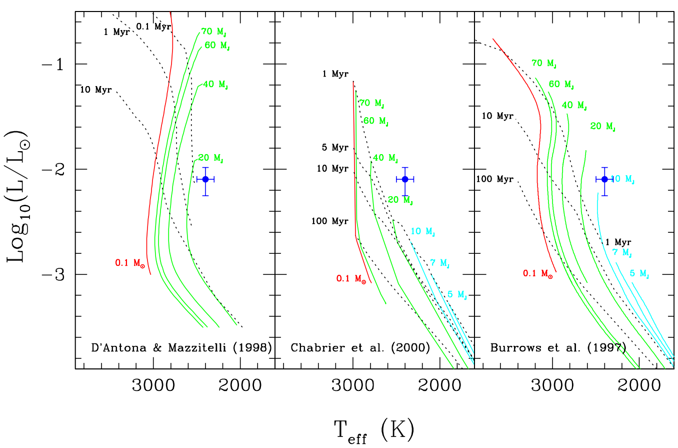

Fig. 2.— Hertzprung-Russell diagram for three sets of evolutionary tracks (D'Antona & Mazzitelli 1997; Chabrier et al. 2000; Burrows et al. 1997). The position of GY11 is shown as a blue circle. The tracks are labelled with the appropriate mass, hydrogen burning stars are shown in red, deuterium burning brown dwarfs in green, and objects below the deuterium burning limit in cyan. Isochrones are shown as dotted lines and are labelled with the appropriate ages.

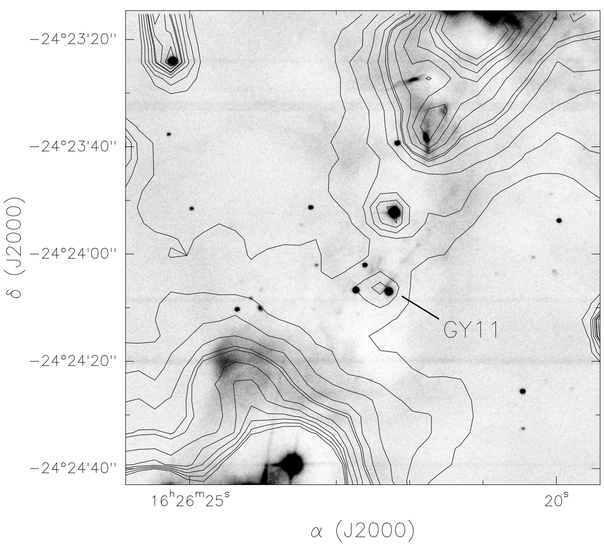

Fig. 3.— The ISOCAM-LW1 (contours, 4.5μm) image of the region surrounding GY11 is overlaid on the VLT K$_s$ (greyscale, 2.2μm) image. The ISOCAM image has been aligned with the VLT image by matching the position of GY10 (2320.8-1708, Comerón et al. (1998)) with the associated mid-infrared source.

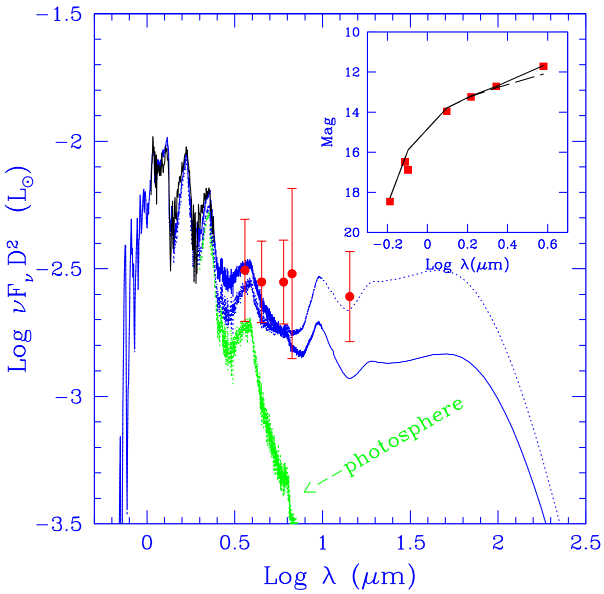

Fig. 4.— Disk and photosphere model of the GY11 SED. The red circles with errorbars show the mid-infrared fluxes from ISOCAM (Comerón et al. 1998; Bontemps et al. 2001), the black line is our NIR dereddened Amici spectrum. The green jagged line is the photospheric model for T_{eff}=2400 K and Log(g)=3.5 (Allard et al. 2000). The blue lines show the combined photosphere plus disk emission computed as in the text. In one case (solid line) the disk inner radius is equal to $R_\star$, in the other (dotted line) to $3R_\star$. In the inset, we show the comparison between the dereddened broad band photometry (from R to L′; red squares) and the models (practically coincident), photosphere as a dashed line, photosphere plus disk as solid line.